PULSED POWER APPLICATIONS IN AIRCRAFT LIGHTNING QUALIFICATION TESTING

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Abstract

Lightning qualification testing relies on a variety of pulse power generators to produce the waveforms necessary to assess the effects of lightning on aircraft and other aerospace systems. The waveforms necessary to produce the significant effects of natural lightning were determined in airborne characterization programs and are specified in DoD military and FAA standards. This paper overviews waveforms and the pulse power generators applied to lightning qualification testing in terms of their type and general characteristics.

Introduction

Combinations of high voltage (mega-volt) and high current (200 kA) pulsed power generators have routinely been employed in military lightning qualification tests for over 30 years. Recent airborne lightning characterization programs have better defined the lightning threat to aircraft and have identified those significant electrical parameters which must be produced to assess lightning's effects on aerospace vehicles. This better understanding of the lightning threat has resulted in new and updated Department of Defense (DoD), military, and Federal Aviation Administration (FAA) standards for test techniques and waveforms required for the lightning qualification testing of military, commercial, and general aviation aircraft. During this period, pulsed power generators have been developed by the government and the major airframers to produce these required waveforms. This paper reviews these test techniques and waveforms in terms of the types and characteristics of the pulsed power generators applied to aircraft lightning qualification testing.

Lightning Simulation/Qualification Testing

The goal of lightning simulation and lightning qualification testing in the Air Force and the aerospace industry is to ensure safety of flight. The adequacy or realism of lightning simulation and qualification tests is limited by our knowledge of the complexities of the natural lightning threat environment during attachment to the aerospace vehicle and the capabilities of the pulsed power lightning simulator generator's to produce those significant effects caused by the interaction of the aircraft with the lightning flash. The effects are broadly classified as direct effects and indirect effects. Direct effects are physical damage such as burning, blasting, pitting, and structural deformation, while indirect effects are damage or upset to electrical/electronic systems caused by the electromagnetic coupling of lightning's energy into the interior of the aircraft. The introduction of lightweight advanced composite materials which do not provide the levels of protection previously afforded by all metal aircraft and the increasing use of advanced digital electronics to perform critical safety of flight functions has increased interest in performing more accurate lightning simulation tests.

Because of its significance to lightning simulation and qualification testing, several lightning characterization programs have been undertaken to characterize the natural lightning environment and to measure its interaction with aircraft. The most recent of these efforts include the Air Force/NOAA WC-130, Air Force/FAA CV-580, and the NASA F-106 programs. Lightning measurements recorded during these airborne programs has been combined with ground measurements on tower to provide a definition of the natural lightning threat environment.

Lightning measurements made during these programs has shown that natural lightning is a complex and variable phenomena. This data has revealed that while it is extremely difficult, if not impossible, to simulate a complete lightning flash the most significant voltage and current characteristics of lightning can be produced separately with pulsed power impulse generators. The direct and indirect effects of lightning can be simulated by the production of four of its parameters.(1) They are:

- the current peak amplitude (Imax)
- the maximum current rate of change (dI/dt)
- the action integral ($\int i^2 dt$)
- the charge transfer ($\int i dt$)

Present simulation/qualification approached by government and industry attempt to produce lightning's effects not the phenomena.

Lightning Qualification Waveforms

Because of the complex nature of natural lightning it has long been recognized that standardized lightning qualification waveforms were needed which would reproduce the most critical effects of the lightning/aircraft interaction. Much of the credit for developing these waveforms illustrated in Figure 1 (2) belongs to the SAE-AE4L committee. This committee is comprised of experts in the field of lightning research and protection of aircraft and systems from government and industry, These standardized waveforms combined with the test set-ups developed for lightning qualification tests provide the requirements for pulsed power generators designed and built for this purpose.

The waveforms form the basis of lightning simulation tests required to pass safety qualification for the military and civilian aircraft and are embodied in DoD-STD-1795, MIL-STD-1757A, and FAA Advisory Circular AC-20-53A. Examples of the uses of these waveforms are given in Table 1.

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14. ABSTRACT
Lightning qualification testing relies on a variety of pulse power generators to produce the waveforms necessary to assess the effects of lightning on aircraft and other aerospace systems. The waveforms necessary to produce the significant effects of natural lightning were determined in airborne characterization programs and are specified in DoD military and FAA standards. This paper overviews waveforms and the pulse power generators applied to lightning qualification testing in terms of their type and general characteristics.

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Current components A, B, C, D, and H produce the significant effects of the natural lightning flash. These components are produced either separately or in combinations of two or more. A, B, D, and H are described by double exponential waveforms of the form:

$$I(t) = I_0 \left(e^{-\alpha t} - e^{-\beta t}\right)$$

These waveforms provide the important characteristics of Imax, dI/dt, $\int i^2 dt$, $\int i dt$. Component C is a rectangular current pulse that transfers most of the charge in a lightning flash.

The Pulsed Power Generators

The lightning simulation pulsed power generators required to produce all of these waveforms into a typical full size vehicle/return path set-up at once would be extremely difficult, complex, and costly. The return paths are typically coaxial (as shown in Figure 2) or flat plate. The vehicle/return path arrangements typically represent lumped parameter loads of between 1 and 20 H and a few milli-ohms to several ohms depending on the size and material construction of the vehicle. The generator is required to produce these waveforms into the vehicle/return path. Pulsed power generators typically used for lightning qualification are classified as full scale severe threat generators, scaled moderate threat generators, high voltage generators, high current generators, and other generators. the remainder of this paper discusses the waveforms and typical pulsed power generator required to produce them into a full scale vehicle/ return path configuration during lightning qualification tests.

Full Scale Severe Threat Generators

Full scale severe threat pulse power simulation generators are those generators which are capable of faithfully producing the four significant current parameters into a full scale vehicle/return path configuration. These generators are used to produce waveforms A and D. Waveform A, the most difficult to produce, has a peak amplitude of 200,000 amperes, an action integral of 2 x 10^6 A^2s and a rate of rise of 1 x 10^{11} A/s at 0.5 s and a peak rate of rise of 1.4 x 10^{11} A/s, and is described mathematically by the double exponental waveform with I_0 = 218,810 A, = 11,354 (1/s) and = 647,265 (1/s). The significant characteristics of this waveform and the others are presented in Table 2. This type of generator is the most desirable because it most realistically produces the severe threat characteristics of natural lightning. However, in the United States there are only two generators which can produce component waveform A into a full size aerospace vehicle. These generators include the one located at Sandia National Laboratories (3) and the one built by Maxwell Laboratories for the Air Force Wright Aeronautical Laboratories' Atmospheric Electricity Hazards Protection Advanced Development Program (4). Both of these generators use high voltage, high energy Marx banks in oil and employ a laser-beam-triggered spark gap crowbar switch to provide the unidirectional, long duration, high action integral pulses which form the component A. The basic circuit for these generators is shown in Figure 3. This crowbar switch makes the circuit a lightly damped L-C circuit before closure to provide the high dI/dt on the leading edge of the pulse and then a L-R circuit after closure to provide the long decay time on the trailing edge. The design of this switch which must close when the peak current is maximum is one of the greatest challenges in the design of the full scale severe threat pulsed power generator.

Scaled Moderate Threat Generators

Moderate threat generators produce the A, B, and D waveforms at lower levels of peak current, Imax, typically between 20,000 and 50,000 amperes. These generators are usually smaller triggered Marx generators operated in either oil or air which produce the double exponential waveforms by use of field enhancement triggered spark gap crowbar switches or by an overdamped RLC circuit. These generators are less desirable than the severe threat generators because they do not produce the full scale threat characteristics of natural lightning and the results must be analytically scaled for qualification testing. The most common generators used for lightning qualification testing produce only a couple of the characteristics and they are classified as either high voltage or high current generators.

High Voltage Generators

High voltage generators, other than the sever and moderate threat generator described above are commonly used to determine lightning attachment points on the aircraft and for indirect effects testing on aircraft. MIL-STD-1757A defines the specific attachment zones on an aircraft by the probability of direct attachment of the lightning flash's arc root and specifies the amount of protection required for each zone. Zone 1 areas on the aircraft have a high probability of initial lightning flash attachment (entry or exit). Zone 2 areas are surfaces over which the lightning flash would probably be swept across. Zone 3 areas area all other areas and may be required to carry lightning currents by conduction rather than attachment. The zone determines the design of the type of protection for each section of the aircraft. Arc attachment zones are found by using long arc attachments produced by the classical high voltage Marx banks whose output typically ranges from 300 kV to 6 MV with energies between 250 J and 192 kJ. (5) These Marx are erected and the output produces long arcs which attach to either models, components, or full aircraft to determine attachment zones.

High Current Generators

High current generators trade off voltage and rate of rise to achieve high levels of maximum current and charge transfer. These generators are normally large sets of high energy capacitors arranged in parallel which produce short arc attachments to aircraft structures and components to test for protection against lightning's direct effects.

Other Generators

The variety of other generators used for lightning qualification and protection development is endless. Some produce high current and high voltage by forming Marx banks with parallel capacitors in each stage. Component C is generally produced by large banks of parallel batteries or with motor generator sets. Component E used for indirect effects testing has been produced by generators that employ a peaking capacitor similar to that used for nuclear effects testing. One such generator developed by the Air Force Atmospheric Electricity Hazards Group (AFWAL/FIESL) is capable of producing currents of 20 t0 40 kA with risetimes (0 - 100%) of 100 to 200 nsec into an operational aircraft. (6) A lumped RLC representation of this generator is shown in Figure 4. This generator produces the high dI/dt values required in component E of the standardized waveforms.

Summary

Pulsed power generators have long had extensive application in the lightning qualification of aerospace vehicles. Characterization programs have better defined those characteristics of natural lightning these generators must produce and these have been documented in specifications as standardized waveforms. In practice, a wide variety of pulsed power generators have been applied to produce these waveforms into systems and entire aircraft.

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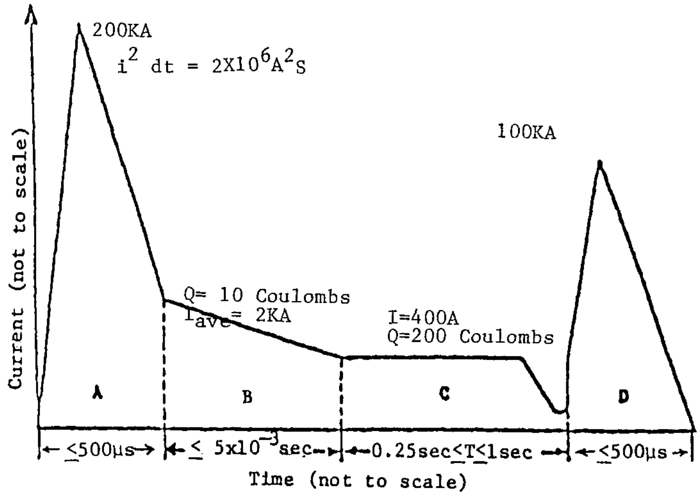
TABLE I

Lightning Waveform Applications

	A	B	C	D	E
Full Size Hardware Attachment Point Tests	X	X	X	X	
Direct Effects Structural Tests	X	X	X	X	
Direct Effects Streamer Tests		X			
Indirect Effects Tests	X			X	X



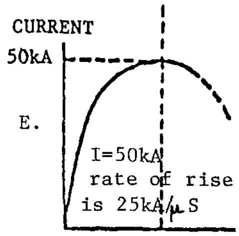


Figure 1. Lightning Qualification Waveforms.

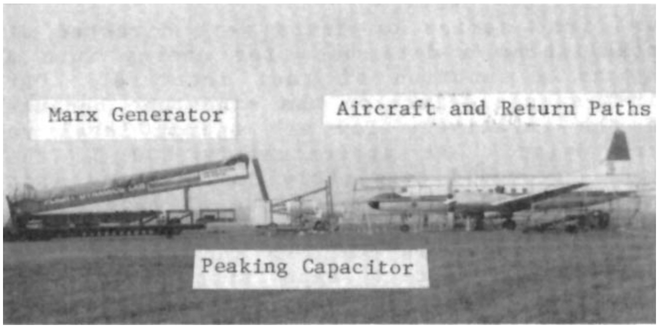


FIGURE 2. A Lightning Qualification Set-Up

TABLE 2 *

Idealized Lightning Qualification Waveform Parameters

Parameter	Waveform A	Waveform B	Waveform C	Waveform D	Waveform E
I_o (A)	218,810	11,300	400	109,405	10,572
α (S^{-1})	11,354	700	N/A	22,708	187,191
β (S^{-1})	647,265	2,000	N/A	1,294,530	19,105,100
Applied to the double exponential equation these produce the following characteristics:					
IMAX	200 KA	4,173 A	400 A	100KA	10KA
(di/dt)max	$1.4X10^{11}$	N/A	N/A	$1.4X10^{11}$	$2X10^{11}$
Action Integral	$s.0X10^6$	N/A	N/A	$.25X10^6$	N/A

* From a report of the SAE-AE4L Committee entitled Protection of Aircraft Electrical/Electronic Systems Against the Indirect Effects of Lightning, dtd Feb 87

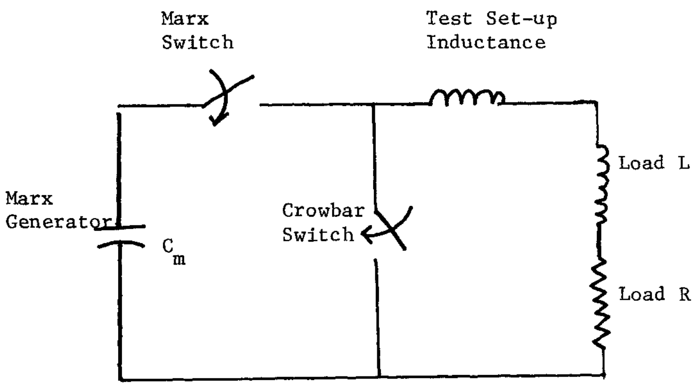


Figure 3. A Basic Crowbar Circuit for Lightning Generators

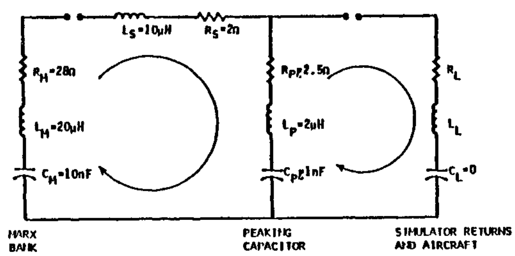


FIGURE 4. A Fast Risetime Generator's Lumped RLC representation.